

A MULTICHANNEL DUAL-MIXER STABILITY ANALYZER: PROGRESS REPORT^{*}

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Abstract

A stability analyzer is being developed for frequency standards in JPL's Deep Space Network. Prototype hardware and software have been built. Initial tests on 100-MHz sources show an Allan deviation noise floor of about 7×10^{-15} at 1 second for a dual-mixer channel.

1 Motivation

JPL operates planetary spacecraft from three Deep Space Communications Complexes: one at Goldstone in the California desert, one near Madrid, and one near Canberra. Each complex has several frequency standards, including hydrogen masers, mercury trapped-ion standards, and cryogenic compensated sapphire oscillators (CSOs). We do not yet have a convenient, reliable method for keeping track of the stabilities of the oscillators at the remote sites. On the other hand, we have operated a multiple-channel measurement system for many years in our laboratory at JPL. In this system, some of the sources to be compared are lowered by 1 Hz in frequency by means of offset generators. These offset sources are mixed against the others to produce 1-Hz beat notes, whose zero crossings are captured by interval timers and converted to phase residuals.

Since the middle 1980s we have deployed a succession of field versions of the laboratory system. Mainly because of computer and software problems, these systems have all been unsatisfactory, being cumbersome, inflexible, unreliable, expensive, and bug-infested in different combinations. In addition, although their noise floor (about 10^{-14} at 1 second) is low enough to characterize H masers and Hg ion traps, it is not low enough to measure (at 100 MHz) the stability of CSOs, estimated to be about 3×10^{-15} at 1 second. For these reasons, we are trying to design and implement a new measurement system, the Frequency Standards Stability Analyzer (FSSA), to meet our needs in the field and eventually, we hope, to replace our aging laboratory system.

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2 System architecture

Our current 1-Hz measurement systems are “single-mixer” systems, in that the phase residuals of different beat notes are not directly compared; to compare two sources, one must connect an offset generator (OSG) to one of them and generate a beat note. To achieve a simpler, cheaper system, yet having a low noise floor, we have gone to a dual-mixer architecture that requires only one offset source to be mixed against all the devices under test (DUTs), which stay on frequency [1]. Figure 1 shows a simplified block diagram of the FSSA. In order to capture the zero crossing times of all the beat notes on a single time scale, we are taking advantage of event timers in the form of PC interface cards that have recently been developed. Our current design uses a Guide Technology sixteen-channel Time Interval Analyzer with a resolution of 20 ns. Up to seven 100-MHz DUTs (one of which will also serve as a reference) will be mixed against the output of the 100-Hz OSG. The eighth auxiliary channel will be used for a source at some other frequency, mixed against a synthesizer or a separate offset source.

3 Offset generator

Figure 2 shows the design of the offset generator we are now using to lower a 100-MHz signal by 100 Hz. It consists of two single-sideband mixer assemblies, separated by a bandpass filter and followed by a phase-locked cleanup loop. The overall principle is summarized by the equation $(1 - x)(1 + x) = 1 - x^2$, where $x = 10^{-3}$. (The same principle, with $x = 10^{-4}$, is used in our 1-Hz systems.). The two mixer assemblies are identical except for a jumper that determines which sideband is extracted (see the plus and minus signs in Fig. 2). The output of the two mixer assemblies has a carrier at 100 MHz – 100 Hz plus spurs with relative amplitude $1/3^2$ (–19 dBc) at carrier +400 Hz, $1/5^2$ at –400 Hz, $1/7^2$ at +800 Hz, $1/9^2$ at –800 Hz, and so forth. The purpose of the cleanup loop is to attenuate these spurs; otherwise, they would affect the zero crossings if a DUT were slightly off frequency, even if it were perfectly stable. In addition, the VCO must have low phase noise; according to Section 5, part of the dual-mixer noise floor comes from the VCO noise in narrow bands about harmonics of the beat frequency.

4 Dual-mixer processing

In the dual-mixer architecture, the phase residuals derived from two individual beat notes (1 and 2, say) are subtracted from each other, giving the phase of source 1 minus the phase of source 2. For the phase of the offset source to be effectively cancelled by this subtraction, the beat frequency (100 Hz in the prototype design) should be considerably greater than the intended measurement bandwidth (default 1 Hz). The zero crossings t_n of one channel give rise to raw single-mixer phase residuals $\xi(t_n)$ (in cycles) by the formula

$$\xi(t_n) = n - \nu_b t_n,$$

where ν_b is the nominal beat frequency. The essential term on the right-hand side is n , which is exactly the total beat phase sampled at time t_n ; the other term is just a gross frequency offset to make the numbers come out smaller. The raw phase residuals of the two channels are then distilled in real time to averaged phase residuals on a uniform time grid with spacing τ_s , the sample period (default 0.5 s, to achieve a 1-Hz bandwidth). Figure 3 shows how this is done by a numerical integration of the linearly interpolated phase residual functions. The τ_s -grid is the same for all

channels, so that the averaged single-mixer phase residuals of two channels, $\bar{\xi}_1(k\tau_s)$ and $\bar{\xi}_2(k\tau_s)$, can be subtracted to give the dual-mixer phase residuals $\bar{\xi}_{12}(k\tau_s)$ for source 1 minus source 2.

5 Noise floor calculations

The two noise floor sources that we have been able to quantify are timer quantization and common-source noise. Their effects are given approximately by the following formulas for the standard deviation of an averaged dual-mixer phase, now in radians:

$$\sigma_{\phi, \text{qu}} = 2\pi q \sqrt{\frac{\nu_b}{6\tau_s}} \quad (\text{quantization}) \quad (1)$$

$$\sigma_{\phi, \text{cs}} \leq \sqrt{2 \sum_{m \neq 0} \frac{|G((m+1)\nu_b)|^2}{|G(\nu_b)|^2} p(m\nu_b)} \quad (\text{common source}) \quad (2)$$

[2], where q is the timer resolution (20 ns), $G(\nu)$ is the transfer function of the lowpass mixing filter, $p(\nu)$ is the spectral power, relative to carrier power, of the offset source in a band of width $1/\tau_s$ at frequency ν from the carrier, and the summation is over all positive and negative m . Assume that $p(m\nu_b)\tau_s \leq -134$ dBc/Hz for $m \neq 0$ (from a measurement of the VCO that we are now using in the cleanup loop), and let G be a single-pole filter with 3-dB bandwidth $3\nu_b$. Then $\sigma_{\phi, \text{qu}} = 5.1 \times 10^{-7}$ radian, $\sigma_{\phi, \text{cs}} \leq 1.2 \times 10^{-6}$ radian. With white PM assumed, these numbers entail Allan deviations 2.0×10^{-15} at 1 second for quantization, 3.4×10^{-15} for common source, giving a total RSS value about 4×10^{-15} , which is close to the performance we desire. To improve it, it might be feasible to trade off these two noise components against each other by adjusting ν_b . Also, we might eventually use a timer with a smaller q , especially in a laboratory system.

This computation does not include the effect of spurs produced by the single-sideband mixers and attenuated by the cleanup loop; although (2) includes their effect on the long-term phase noise variance, their effect on Allan deviation is harder to quantify because they appear as slow phase variations that depend on the behavior of the sources under test. They are unlikely to affect the noise floor below an averaging time of 100 s.

6 Noise floor test

We have built enough hardware and software to set up and evaluate a three-channel prototype system. For our first test, one H maser 100-MHz signal was split into the OSG and the three input channels; the beat notes went to channels 0, 2, and 4 of the event timer card. The bandwidth of the OSG cleanup loop was 3 Hz. Figure 4 shows the result of a 1370-second run. The upper plot shows the first 50 seconds of the phase residuals (scaled to time residuals at 100 MHz) for single-mixer channels 0, 2, and 4 minus the offset source; the middle plot shows the corresponding phase residuals for dual-mixer channels 0-2, 0-4, 2-4. The lower plot shows the Allan deviations of all six phase-residual time series for the whole run. The dual-mixer cancellation makes the 1-second instability smaller by a factor between 29 and 38. As averaging time increases, however, the dual-mixer phase residuals depart more and more from a white PM model; we hope to be able to reduce these longer-term noise effects.

7 Conclusions

The very first noise floor test, without any further adjustments, gave stability results that are about the same as those from our laboratory 1-Hz measurement system, about 7×10^{-15} at 1 second. Although this is about a factor of two greater than where we want to be, it is adequate for all our frequency sources except CSOs at 100 MHz; two of these, however, can be tested separately at 800 MHz in the auxiliary single-mixer channel because their design incorporates an output synthesizer.

Attempts to improve the system are underway. We have not yet experimented with the cleanup-loop bandwidth. It might be feasible (and it would certainly be cheaper) to use a commercial synthesizer in place of the in-house offset generator; in that case, the beat frequency would be easily adjustable. We have not yet decided on the computer and software architecture, so much a problem in the past.

In summary, we assert that the FSSA design has been validated, and we intend to proceed with improvements, development, and production during the coming year.

References

- [1] S. Stein, D. Glaze, J. Gray, D. Hilliard, D. Howe, and L. A. Erb, "Automated high-accuracy phase measurement system," *IEEE Trans. Instrum. Meas.*, Vol. 32, No. 1, pp. 227–231, March 1983.
- [2] C. A. Greenhall, "Common-source phase noise of a dual-mixer stability analyzer," *TMO Progress Report 42-143*, Jet Propulsion Laboratory, Pasadena, CA, Nov. 2000 (http://tmo.jpl.nasa.gov/tmo/progress_report/42-143/143K.pdf).

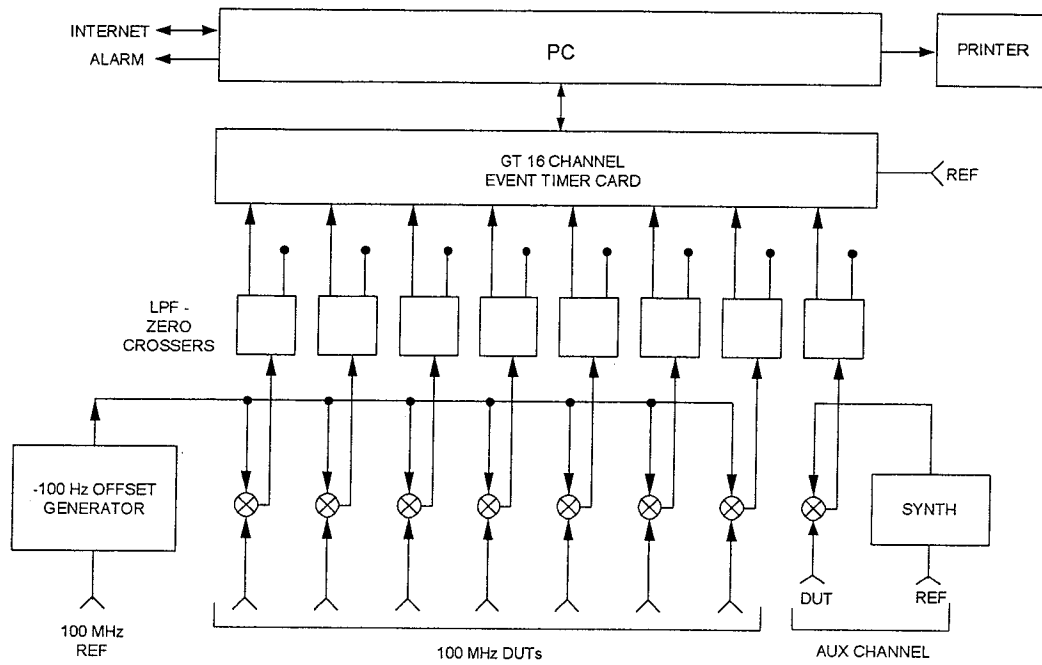


Fig. 1. Stability analyzer architecture

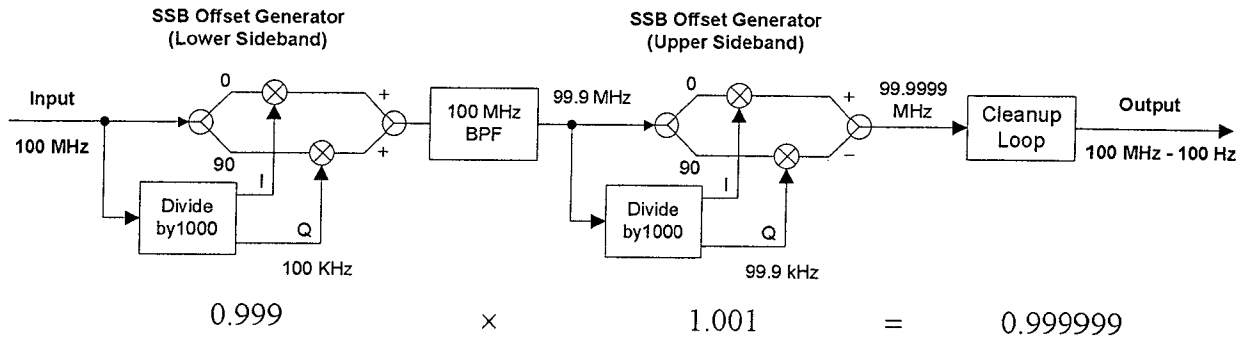


Fig. 2. Offset generator for lowering a 100-MHz source by 100 Hz. Two cascaded single-sideband mixers are followed by a phase-locked cleanup loop with a low-noise VCXO.

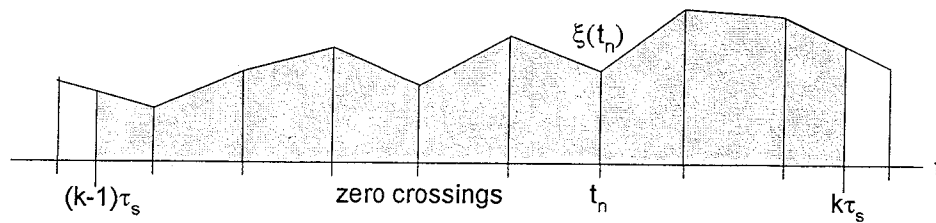


Fig. 3. A beat-note zero crossing at t_n gives rise to a phase residual $\xi(t_n)$. Between the zero crossings, the phase is interpolated linearly. The average phase for the interval $[(k-1)\tau_s, k\tau_s]$ is the shaded area divided by τ_s .

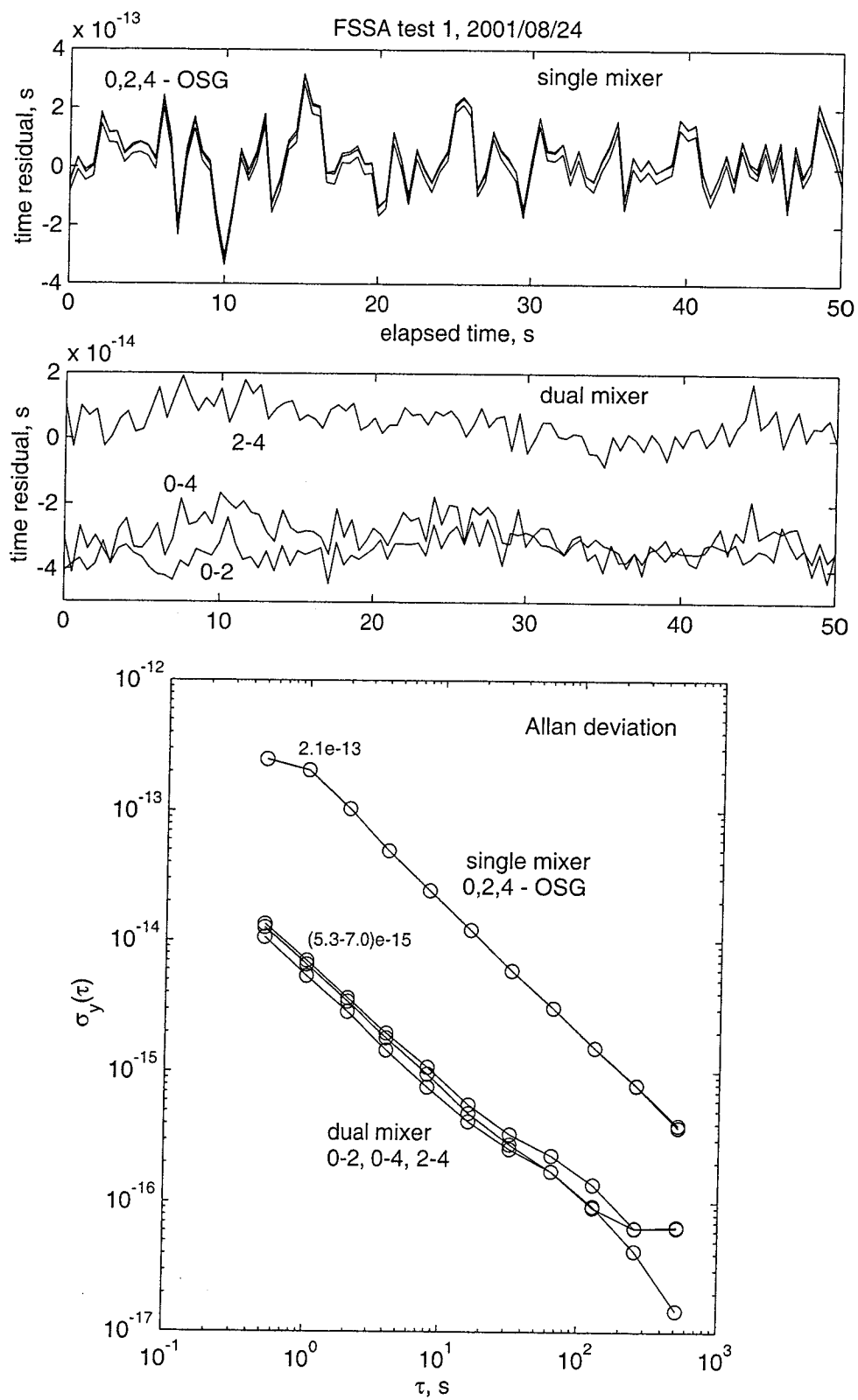


Fig. 4. Results of the first noise floor test